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Structural Health Monitoring Activities at Los Alamos National Laboratory

Hoon Sohn and Charles R. Farrar
Los Alamos National Laboratory, Los Alamos, New Mexico

Throughout the workshop, the importance of instrumentation for bridges and dams had been pointed out numerous times. Many workshop participants seemed to agree that the recorded data provide invaluable information to assess the integrity and life safety of civil infrastructure, and help to improve the scientific understanding about the dynamic response of structures under extreme events such as earthquakes. The advances in sensing and communication technologies are making the instrumentation of densely spaced sensors not only feasible but also practical. Furthermore, the workshop participants have put recommends to encourage building owners and bridge operators to install more instrumentation. There was, however, very little discussion on how to utilize these immense amounts of data collected. Taking into account the increasing demand for real or near-real time damage assessment, the issues of data mining and interrogation of the expected huge amount of measurement data becomes a very critical issue.

This need for quantitative damage detection and assessment has led Los Alamos National Laboratory (LANL) to research into Structural Health Monitoring (SHM) methods that can be applied to complex structures. The SHM process involves the observation of a structure over a period of time using periodically spaced measurements, the extraction of features from these measurements, and the analysis of these features to determine the current state of health of the system. The output of this process is periodically updated information regarding the ability of the structure to continue to perform its desired function in light of the inevitable aging and degradation resulting from the operational environments. Vibration-based damage detection is a tool that is receiving considerable attention from the research community for such monitoring.

The basic premise of vibration-based damage detection is that the damage will significantly alter the stiffness, mass or energy dissipation properties of a system, which, in turn, will alter the measured dynamic response of that system. Staff at Los Alamos National Laboratory cast the process of vibration-based structural health monitoring into a statistical pattern recognition paradigm, and this statistical process is composed of four portions: (1) Operational evaluation; (2) Data acquisition and cleansing; (3) Feature selection and data compression, and (4) Statistical model development. More detailed discussion of the statistical pattern recognition paradigm can be found in Farrar et al, 2000.

The presentation focuses on the feature extraction and statistical model development aspects of the statistical paradigm. A novel time series analysis procedure is presented to identify the presence of damage and to localize damage sources in a structural system (Sohn and Farrar, 2000). An attempt is made to pinpoint the sources of nonlinear damage by solely analyzing the vibration signatures recorded from a structure of interests. First, a linear prediction model, combining Auto-Regressive (AR) and Auto-Regressive with eXogenous inputs (ARX) techniques, is estimated using a time series recorded under an undamaged stage of the structure. Then, the residual error, which is the difference between the actual time measurement and the prediction from the previously estimated AR-ARX combined model, is defined as our damage-sensitive feature. This study is based on the premise that if there were damage in the structure, the prediction model previously identified using the undamaged time history data would not be able to reproduce the newly obtained time series data measured under a damaged state of the structure. Furthermore, the increase of the residual errors would be maximized at the sensors instrumented near the actual damage locations. The applicability of this approach is demonstrated using the vibration test data obtained from an eight degrees-of-freedom (DOF) mass-spring system.

The same AR-ARX procedure is applied to the fiber optic strain gauge data obtained from two different structural conditions of a surface-effect fast patrol boat. The surface effect ship is a pre-series fast patrol boat built by Kvaerner Mandal in Norway. Together with a research team from the Norwegian Defense Research Establishment (NDRE), the ship designers determined the optimal sensor placement. The sensor installation and data acquisition during sea trials was performed jointly by NDRE and Naval Research Laboratory (NRL). Fiber optic strain gauges with Bragg grating were used to measure the dynamic response of the ship. The boat and the associated data acquisition are summarized in Wang and Pran (2000). The main objective is to extract features and to construct a statistical model that distinguishes the signals recorded under the different structural conditions of the boat. Three strain time-histories obtained from two different structural conditions were transmitted to the staff at LANL from NRL. It was explained that the first two signals, Signal 1 and Signal 2, hereafter, were measured when the ship was in “Structural Condition 1” while Signal 3 was measured when the ship was in “Structural Condition 2”. However, it was not told which sensor these data came from. LANL staff was not informed of any data cleansing or data normalization that was performed prior to the transmission of these signals to LANL. It is assumed that these data were acquired under varying environmental and operational conditions. Changing environmental conditions can include varying sea states and thermal environments associated with the water and air. Changing operational conditions include ship speed and the corresponding changes in engine performance, mass associated with varying ship cargo, ice buildup and fuel levels, and maneuvers the ship undergoes. No measures of these environmental or operational conditions were provided.

The goal of this investigation is to normalize these data and extract the appropriate features such that Signal 3 could be clearly discriminated from Signals 1 and 2. Also, it must be shown that the same procedure does not discriminate Signal 1 from Signal 2. Following the proposed local ARX technique, this study successfully identifies features from the strain time histories that distinguish Signal 3 from Signals 1 and 2 (see Figure 2). The feature employed in this study, the standard deviation ratio, showed a clear distinction between Signal 3 and Signals 1 and 2. Also Signals 1 and 2 appeared to be similar when compared through this feature. To validate the proposed approach, 80 signal segments are randomly sampled for damage classification. Out of 80 tested cases, there were only 4 misclassifications. That is, 95% of the tested signal blocks are correctly assigned to their actual structural conditions. Finally, out of 40 segments obtained from Signals 1 and 2, there were only one false-positive indications of damage and the rest of 39 cases are correctly assigned to “Structural Condition 1.” That is, with this proposed procedure, a clear distinction between the two different structural conditions was achieved. The presented approach is very attractive for the development of an automated monitoring system because of its simplicity and no interaction with users. Furthermore, because damage diagnosis is conducted independently at an individual sensor level, time synchronization among the multiple sensors is not necessary.

The goal of the next research effort is to develop a robust and cost-effective SHM device by integrating and extending technologies from various engineering and information technology disciplines. The system will be composed of both hardware and software components (see Figure 3). Changes in dynamic response resulting from damage will be detected with sensitive, dynamic response measurements made with Micro-Electro Mechanical Systems (MEMS) sensors. Firmware for data interrogation will incorporate statistical pattern recognition algorithms presented in this presentation to identify and locate the damage. The firmware will be integrated into the SHM device unit through a programmable micro-processing chip. The processed data output of these sensing units will be monitored at a central location using a wireless data transmission system. This integrated system will be developed with the intent that it can be adapted to monitor a variety of engineering systems. These systems include aircraft, space vehicles, rotating machinery in semi-conductor manufacturing facilities, and buildings and bridges in high seismic regions. Our strategy offers a potential for a significant breakthrough in SHM technology through an integrated sensing/data interrogation process that has not been attempted to date.

References

[1] Farrar, C. R., Duffey, T. A., Doebling, S. W., Nix, D. A., "A Statistical Pattern Recognition Paradigm for Vibration-Based Structural Health Monitoring," Proceedings of the 2nd International Workshop on Structural Health Monitoring, Stanford, CA, USA, pp. 764-773, September 8-10, 2000.

[2] Wang, G. and Pran, K., "Ship hull structure monitoring using fiber optic sensors," *Proceedings of European COST F3 Conference on System Identification & Structure Health Monitoring*, Vol. 1, pp. 15-17, Universidad Politécnica de Madrid, Spain, 2000.

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Figure 1: A surface-effect fast patrol boat

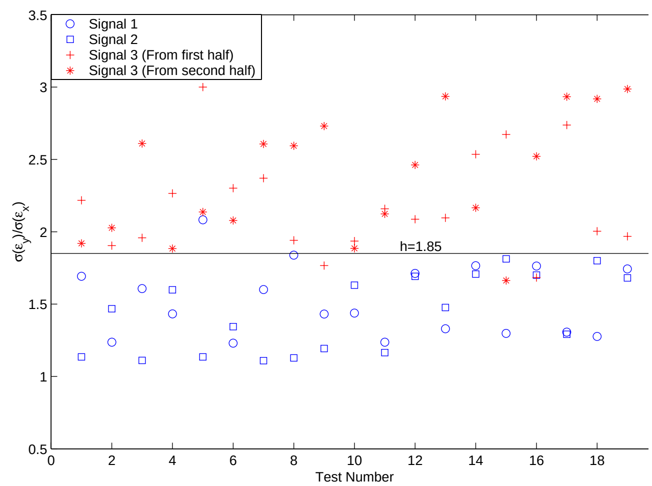

Figure 2: Separation of Signal 3 from Signals 1 and 2 using the ARX residual errors

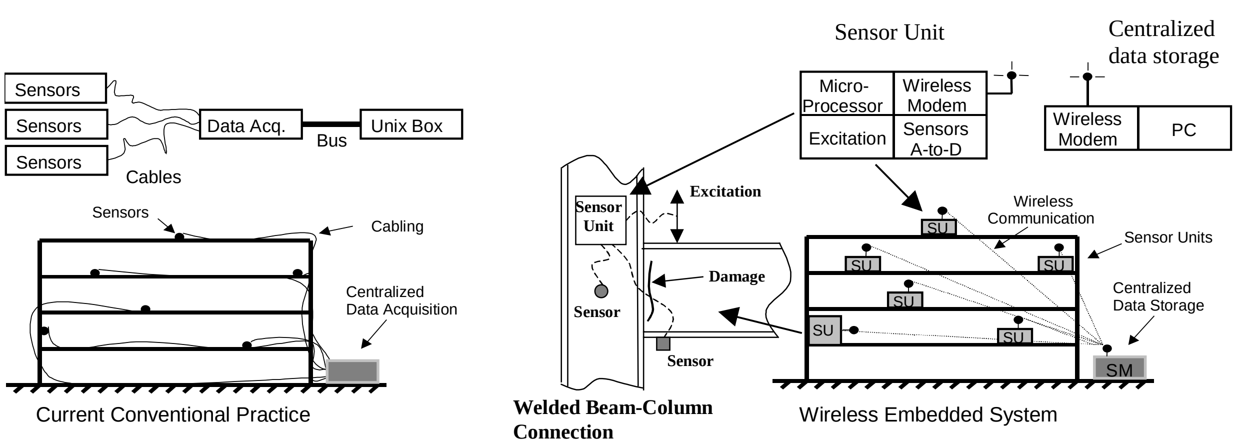

Figure 3: Research Objective: Move from a conventional wired sensing system to an active wireless system